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3.2 MILLIMETER WAVE TRANSMITTER TUBE.(U)
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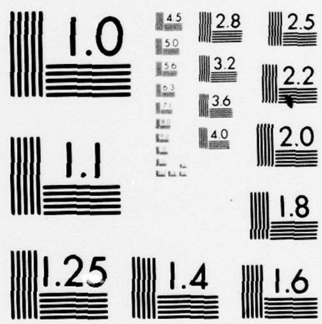
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Research and Development Technical Report
DELET-TR-78-3015-1

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3.2 MILLIMETER WAVE TRANSMITTER TUBE

Ken Arnold

HUGHES AIRCRAFT COMPANY
Electron Dynamics Division
3100 West Lomita Boulevard
Torrance, California 90509

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Pulse Amplifier
Coupled Cavity Traveling Wave Tube

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Design trade-offs have been performed for 95 GHz coupled-cavity traveling wave tubes for two pulse power levels, 100 watts and 1000 watts, respectively. Results indicate that average power levels of 50 watts are feasible in the 100 watt peak power case and that 10 watt average power levels are feasible in the 1000 watt peak power case.

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1. INTRODUCTION

The objective of this program is the development of 3.2 millimeter wave tubes having the smallest possible volume, lowest possible weight, and the lowest potential production cost without compromise of performance. The tube objectives are:

Peak RF power output	1 kW (maximum)
	100 W (minimum)
Average RF power	50 W (liquid cooled)
	Concurrent with 100 W peak
	10 W (air cooled)
	Concurrent with 1 kW peak
Center frequency	93.75 GHz
Instantaneous bandwidth	4%
Small signal gain	60 dB
Large signal gain	50 dB
Pulse length	25 μs max, 1-10 ns objective
Pulse rise time	< 1 μs
PRF	20 KHz max
Length	approx 61 cm
Width	< 10 cm
Height	< 10 cm
Weight	< 7 kg

The program consists of two parallel phases, the first being concerned with the 100 W TWT and the second with the 1 kW TWT.

It is important to view this development program against the background of other millimeter wave TWTs. Hughes has already developed coupled cavity TWTs at 94 GHz. The 1 kW peak model, designated the 980H, has a liquid cooled collector and RF output stack, whereas the 200 W peak model,

the 981H, has only a liquid-cooled collector. The beam voltages are 40 kV and 15.5 kV respectively; however, both tubes utilize solenoid focusing, resulting in a total tube weight in each case of about 100 lbs. For a small volume, low weight device, the use of periodic permanent magnets for beam focusing is necessary. Thus the ability to focus the electron beam becomes a primary constraint.

The magnetic field increases slightly with beam voltage and with the current density at the cathode. Increasing the beam voltage and the current density results in a lower value of γ_a, the propogation constant. This in turn means a greater bandwidth. Thus a smaller, more reliable device (i.e., one which would have in general a lower beam voltage and a lower cathode current density) is more likely to have a narrower bandwidth.

In this report the interdependence of parameters for 93.75 GHz TWTs from 100 W - 1000 W are presented, together with the technical assumptions which have been made.

2. TECHNICAL DISCUSSION

2.a PARAMETER SELECTION

In the present TWT designs at mm wavelengths a primary constraint is beam focusing, to be accomplished by periodic permanent magnets. After defining acceptable focusing criteria, the initial task is to establish the operating voltage for highest interaction strength.

Interaction Strength Versus Focusing Constraint

A quantitative measure of the effective interaction strength is Pierce's growth parameter C given by

$$C = \left(\frac{KI_o}{4V_o}\right)^{1/3} \tag{1}$$

where

- K = Pierce's interaction impedance
- I_o = beam current
- V_o = beam voltage

In PPM focusing both the magnitude of the magnetic field and its period determine the dynamics of the focused beam. The magnetic field, B, required to focus an electron beam from a gun, with thermal velocity effects included, is

$$B^2 = B_b^{\,2} + \frac{8kT_c}{m\eta^2}\left(\frac{r_c^{\,2}}{r_o^{\,4}}\right) + \left(\frac{B_c r_c^{\,2}}{r_o^{\,2}}\right)^2 \tag{2}$$

where

$$B_b^{\,2} = \frac{2I_o}{\pi\varepsilon_o \eta u_o} \frac{1}{r_o^2}$$

$$\eta = \frac{e}{m}$$

Here e and m are the electronic charge and mass respectively, ε_o is the permittivity of free space, and k is the Boltzmann constant. The electron beam is described by the total current I_o, the electron velocity u_o, and a certain statistical rms beam radius r_o. The beam starting conditions are specified by the cathode temperature T_c (in degrees Kelvin), the cathode (disk) radius r_c, and the axial field at the cathode, B_c. For a PPM system the field magnitude B in eq. (2) is to be identified with the root-mean-square value.

Comparing the expression for the interaction strength parameter C with the "Brillouin" part, B_b, of the magnetic field, it is evident that the conditions that provide a large C (high current, low voltage) require a strong focusing field. A high interaction impedance K can be obtained with a small beam hole and this again necessitates a strong focusing field. Thus the interaction strength is limited by the magnetic field that can be achieved. It is also seen that the required focusing field goes up with increased cathode size, increased cathode flux, and higher cathode temperature.

The beam stability in a PPM focusing field involves the relation between the oscillation wavelength of the radial motion in the beam and the period of the magnetic field. With a highly thermal low perveance beam, an appropriate oscillation wavelength is that associated with the small-amplitude ripple in r_o given by the angular frequency

$$\omega_R = \omega_c \sqrt{1 - \frac{1}{2} (B_b/B)^2} \tag{3}$$

where

$$\omega_c = \eta B = \text{the cyclotron frequency.}$$

The scallop wavelength is therefore

$$\lambda_s = \frac{u_o}{(\omega_R/2\pi)} = \frac{2\pi u_o}{\omega_c \sqrt{1 - \frac{1}{2} (B_b/B)^2}} \tag{4}$$

If λ_s is large relative to the magnetic field period, L, the beam will effectively experience an average constant focusing field of magnitude B. As λ_s becomes more comparable to L, the electron motion is more affected by the local changes in the field.

When λ_s equals L an unstable beam generally results. To provide good focusing it is therefore necessary to ensure some minimum value of the ratio λ_s/L. Based on prior experience with low perveance thermal electron beams this ratio was chosen as 1.2. Since λ_s is approximately inversely proportional to B, a large C (which requires a large B) will give a small λ_s. The condition $\lambda_s/L \geq 1.2$ thus provides a further constraint on the interaction strength that can be obtained.

General Assumptions

The following general assumptions are made:

1. The PPM structure is external to the vacuum envelope. The magnetic and electrical periods are therefore independent.

2. Samarium Cobalt magnet material is used for maximum field capability.

3. The maximum pole piece field allowed is 1.3 tesla to avoid possible saturation effects.

4. The cathode material was to be impregnated tungsten, with an approximate operating temperature of 1400^{o} K.

5. The focusing design assumed no magnetic cathode flux, $B_c = 0$, since the available magnetic field was a constraint.

6. The ratio of scallop wavelength to magnetic period, λ_s/L, was taken to be 1.2 minimum, as discussed in the preceding section.

7. The beam hole size, 2a, was chosen to transmit (typically) 99.5 percent of the theoretical DC beam. Thus

$$a = r_{99.5,\ max}$$

where $r_{99.5,\ max}$ is the maximum value of the radius that encloses 99.5 percent of the current in the focused thermal DC beam. With no cathode flux, the rms radius r_o is 0.42 of $r_{99.5,\ max}$.[2] Although the concept of a quantitative beam filling factor, b/a, is generally unsatisfactory for a thermal beam, a value of b/a = 0.42 was used in the RF calculations.

Outline of Design Procedure

The general design procedure is outlined as follows:

1. An initial basic tube efficiency is assumed, and the smallest practical ferrule hole size in the PPM stack is estimated.

2. The obtainable magnetic field as a function of magnetic period is evaluated. Using this function and the known DC beam power, relevant properties of the focused thermal beam ($r_{99.5}$, λ_s, and λ_s/L) can be calculated versus the rms focusing field for different beam voltages. The data can be displayed as beam hole radius versus beam voltage at a given λ_s/L. Equivalently, the beam hole size can be expressed in terms of the radial propagation parameter γa, once an appropriate ratio between the beam velocity and the circuit phase velocity at the design center frequency has been chosen.

3. The cavity dimensions and interaction impedance can now be computed for any beam voltage by making some additional assumptions regarding the cold passband characteristics and the cavity geometry. These assumptions concern the cold bandwidth, phase shift per cavity at center frequency, the detailed shape of the frequency vs phase curve, the gap to period ratio, the tunnel wall and web thicknesses, and the coupling hole size. The resulting cavity diameter is checked for compatibility with the assumed magnetic ferrule hole size in Step 1.

4. Knowing the value of Pierce's interaction impedance (averaged over the beam area, assuming $b/a = 0.42$), the variation of Pierce's C parameter with voltage is derived. The operating voltage is chosen to maximize C for highest interaction

strength. At this point all the information necessary to start the detailed electron gun design has also been generated in the process.

5. The small signal gain bandwidth is calculated and the cold passband adjusted if necessary (Step 3). Such an adjustment will generally change the magnitude of the C parameter, but, apart from a constant factor, the variation with voltage will very nearly remain the same.

6. Large signal analysis is performed with various velocity taper configurations in the RF circuit to achieve a high interaction efficiency over the frequency band. If the minimum efficiency differs appreciably from the one assumed in Step 1, another iteration of the design procedure should be made.

2.b 93.75 GHz DESIGNS

The shape of the frequency vs phase (W-β) curve is needed for the impedance calculation. For the 93.75 GHz design, it is assumed that the W-β shape measured for a final circuit at 85 GHz (NASA contract CR EDD W-06553) can be obtained for 93.75 GHz by appropriate cathode loading. A basic efficiency of 5% has also been assumed.

Table I gives the values of particular parameters for a 100 W tube with a beam voltage of 22 kV as a function of the current density at the cathode. Table II gives the same parameters for the same 100 W tube with the beam voltage raised to 25 kV. The values in Tables I and II are displayed in Figures 1 and 2 in terms of the beam voltage, so that the effect of a beam voltage change can be more easily seen.

TABLE I

DESIGN PARAMETERS FOR A 93.75 GHz TWT
POWER OUT = 100 W BEAM VOLTAGE = 22 kV
BEAM CURRENT = 90.9 mA PERVEANCE = .0279 μP

Current Density A/cm^2	J_C	1	2	4	6	8
Cathode radius (in)	τc	.0669	.0473	.0335	.0273	.0237
Beam hole diameter (in)	2a	.0232	.0200	.0175	.0163	.0155
γa		2.016	1.738	1.520	1.416	1.347
C		.01502	.01730	.01925	.02023	.02090
Peak field (gauss)	Bp	4320	4400	4450	4500	4550
Magnetic period (in)	L	.364	.370	.374	.378	.382

TABLE II

DESIGN PARAMETERS FOR A 93.75 GHz TWT
POWER OUT = 100 W BEAM VOLTAGE = 25 kV
BEAM CURRENT = 80 mA PERVEANCE = .0202 μP

Current Density A/cm^2	J_C	1	2	4	6	8
Cathode radius (in)	τc	.0628	.0444	.0314	.0256	.0222
Beam hole diameter (in)	2a	.0219	.0188	.0164	.0151	.0144
γa		1.783	1.531	1.335	1.229	1.172
C		.01556	.01767	.01942	.02040	.02094
Peak field (gauss)	Bp	4440	4500	4570	4620	4650
Magnetic period (in)	L	.373	.378	.384	.388	.390

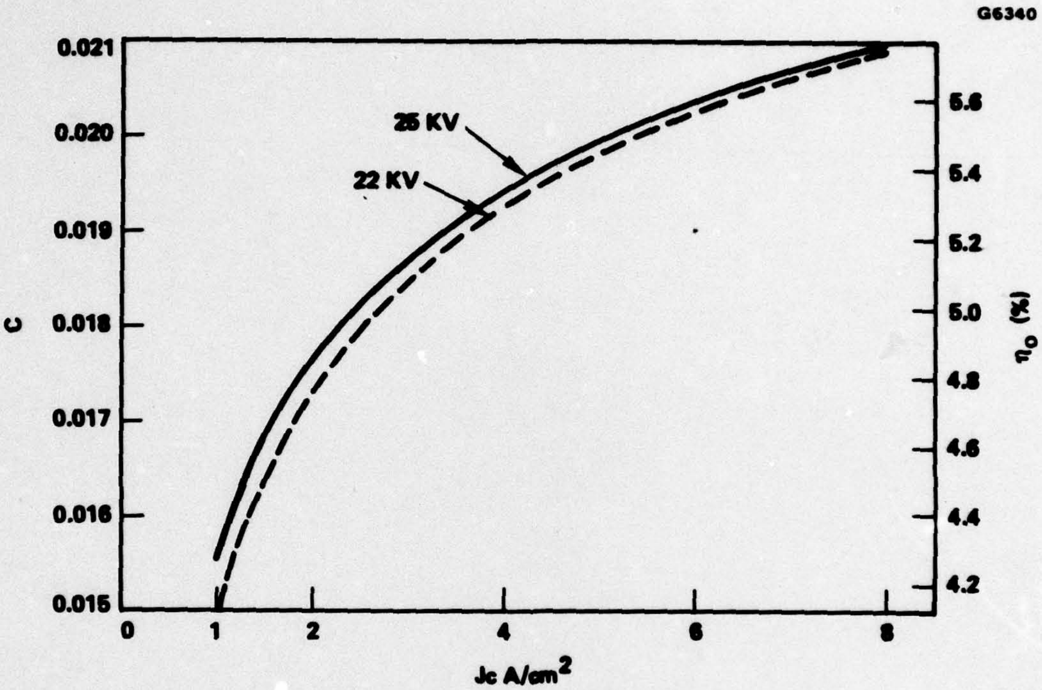

FIGURE 1 VARIATION OF C AND η_o WITH Jc FOR A 100 W TWT WITH DIFFERENT BEAM VOLTAGES.

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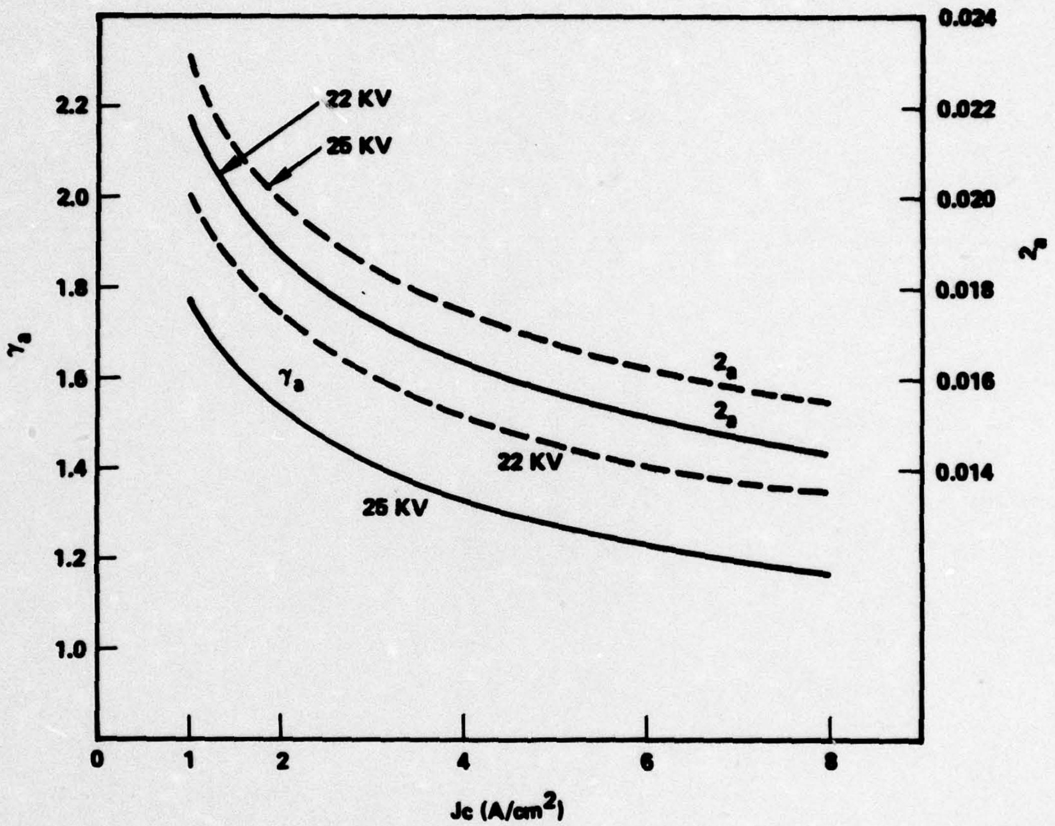

FIGURE 2 VARIATION OF γ_a AND 2_a WITH Jc FOR A 100 W TWT WITH DIFFERENT BEAM VOLTAGES.

Tables III and IV give the parametric values for a 200 W tube for beam voltages of 25 and 30 kV as a function of current density at the cathode. These values are displayed in Figures 3 and 4 in terms of beam voltage.

Tables V, VI and VII give the parametric values for a 500 W tube with beam voltages of 25, 30 and 35 kV respectively, with these values displayed in Figures 5 and 6 as a function of beam voltage. Tables VIII, IX and X give the parametric values for a 1000 W tube with beam voltages of 35, 40 and 45 kV, with these values displayed in Figures 7 and 8.

TABLE III

DESIGN PARAMETERS FOR A 93.75 GHz TWT
POWER OUT = 200 W BEAM VOLTAGE = 25 kV
BEAM CURRENT = 160 mA PERVEANCE = .0405 μP

Current Density A/cm^2	J_C	1.6	2	4	6	8
Cathode radius (in)	τc	.0702	.0628	.0444	.03625	.0314
Beam hole diameter (in)	2a	.0242	.0233	.0203	.0189	.0181
γa		1.970	1.897	1.653	1.539	1.474
C		.01780	.01849	.02095	.02217	.02289
Peak field (gauss)	Bp	4530	4530	4650	4730	4770
Magnetic period (in)	L	.384	.384	.390	.397	.400

TABLE IV

DESIGN PARAMETERS FOR A 93.75 GHz TWT
POWER OUT = 200 W BEAM VOLTAGE = 30 kV
BEAM CURRENT = 133 mA PERVEANCE = .026 μP

Current Density (A/cm^2	J_C	1	2	4	6
Cathode radius (in)	τc	.0811	.0573	.0405	.0331
Beam hole diameter (in)	2a	.0246	.0211	.0184	.0171
γa		1.825	1.565	1.365	1.269
C		.01698	.01942	.02146	.02249
Peak field (gauss)	Bp	4650	4750	4820	4860
Magnetic period (in)	L	.390	.398	.405	.409

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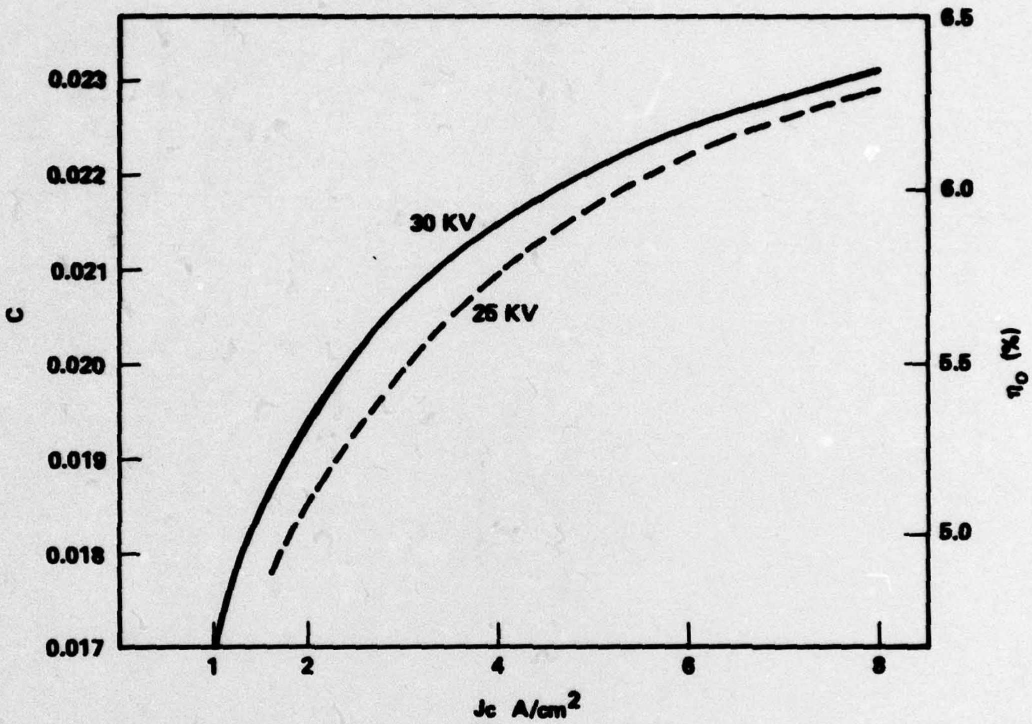

FIGURE 3 VARIATION OF C AND η_o WITH Jc FOR A 200 W TWT WITH DIFFERENT BEAM VOLTAGES.

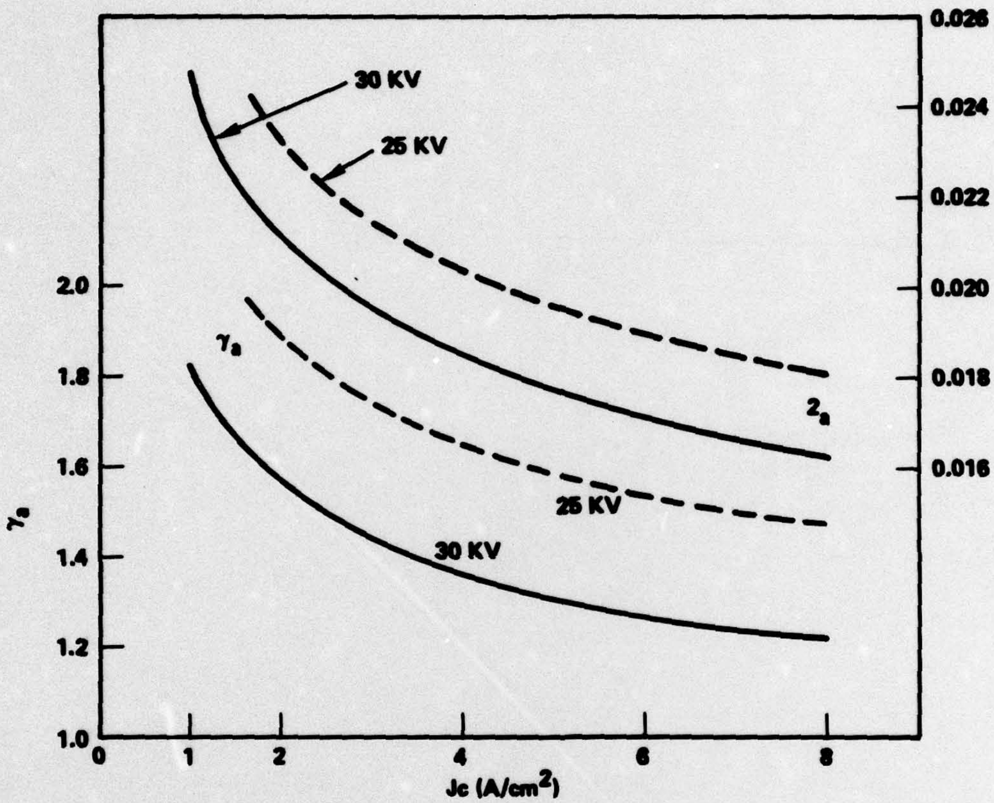

FIGURE 4 VARIATION OF γ_a AND Z_a WITH Jc FOR A 200 W TWT WITH DIFFERENT BEAM VOLTAGES.

TABLE V

DESIGN PARAMETERS FOR A 93.75 GHz TWT
POWER OUT = 500 W BEAM VOLTAGE = 25 kV
BEAM CURRENT = 400 mA PERVEANCE = .1012 μP

Current Density (A/cm^2)	J_C	4	6	8	
Cathode radius (in)	τc	.0702	.0573	.0496	
Beam hole diameter (in)	2a	.0278	.0263	.0255	
γa		2.263	2.141	2.076	
C		.02040	.02175	.02251	
Peak field (gauss)	Bp	4770	4830	4870	
Magnetic period (in)	L	.400	.406	.409	

TABLE VI

DESIGN PARAMETERS FOR A 93.75 GHz TWT
POWER OUT = 500 W BEAM VOLTAGE = 30 kV
BEAM CURRENT = 333 mA PERVEANCE = .0642 μP

Current Density (A/cm^2)	J_C	4	6	8	
Cathode radius (in)	τc	.0641	.0523	.0453	
Beam hole diameter (in)	2a	.0248	.0234	.0224	
γa		1.840	1.736	1.662	
C		.02252	.02377	.02469	
Peak field (gauss)	Bp	4930	4980	5030	
Magnetic period (in)	L	.415	.420	.425	

TABLE VII

DESIGN PARAMETERS FOR A 93.75 GHz TWT
POWER OUT = 500 W BEAM VOLTAGE = 35 kV
BEAM CURRENT = 280 mA PERVEANCE = .0436 μP

Current Density (A/cm^2)	J_C	4	6	8	
Cathode radius (in)	τc	.0593	.0484	.0420	
Beam hole diameter (in)	2a	.0227	.0213	.0203	
γa		1.556	1.460	1.392	
C		.02352	.02470	.02557	
Peak field (gauss)	Bp	5050	5100	5150	
Magnetic period (in)	L	.427	.433	.439	

TABLE VIII

DESIGN PARAMETERS FOR A 93.75 GHz TWT
POWER OUT = 1000 W BEAM VOLTAGE = 35 kV
BEAM CURRENT = 571 mA PERVEANCE = .0873 μP

Current Density (A/cm^2)	J_C	6	8		
Cathode radius (in)	τc	.0685	.0593		
Beam hole diameter (in)	2a	.0272	.0263		
γa		1.865	1.803		
C		.02483	.02565		
Peak field (gauss)	Bp	5200	5240		
Magnetic period (in)	L	.444	.444		

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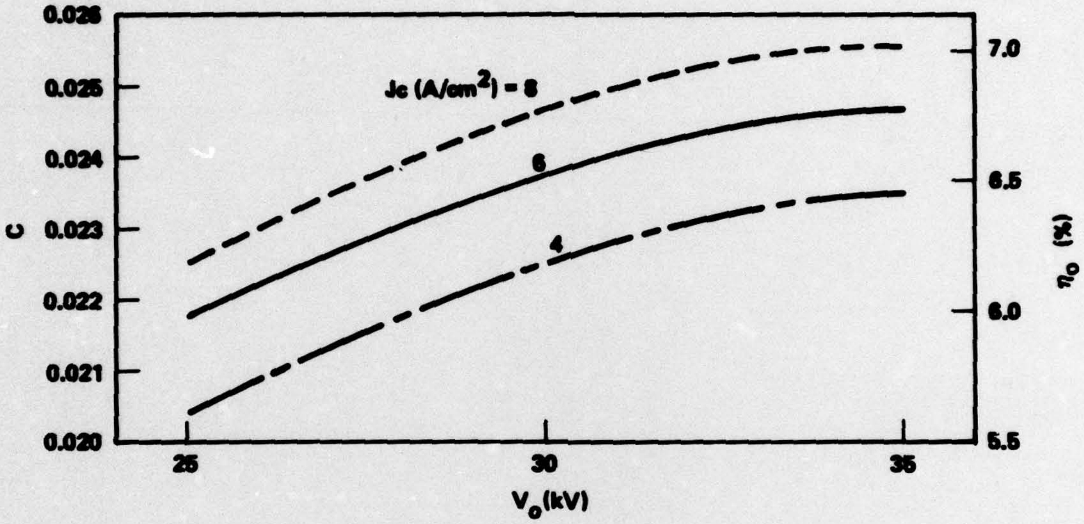

FIGURE 5 VARIATION OF C AND η_o WITH V_o FOR A 500 W TWT WITH DIFFERENT CATHODE LOADINGS.

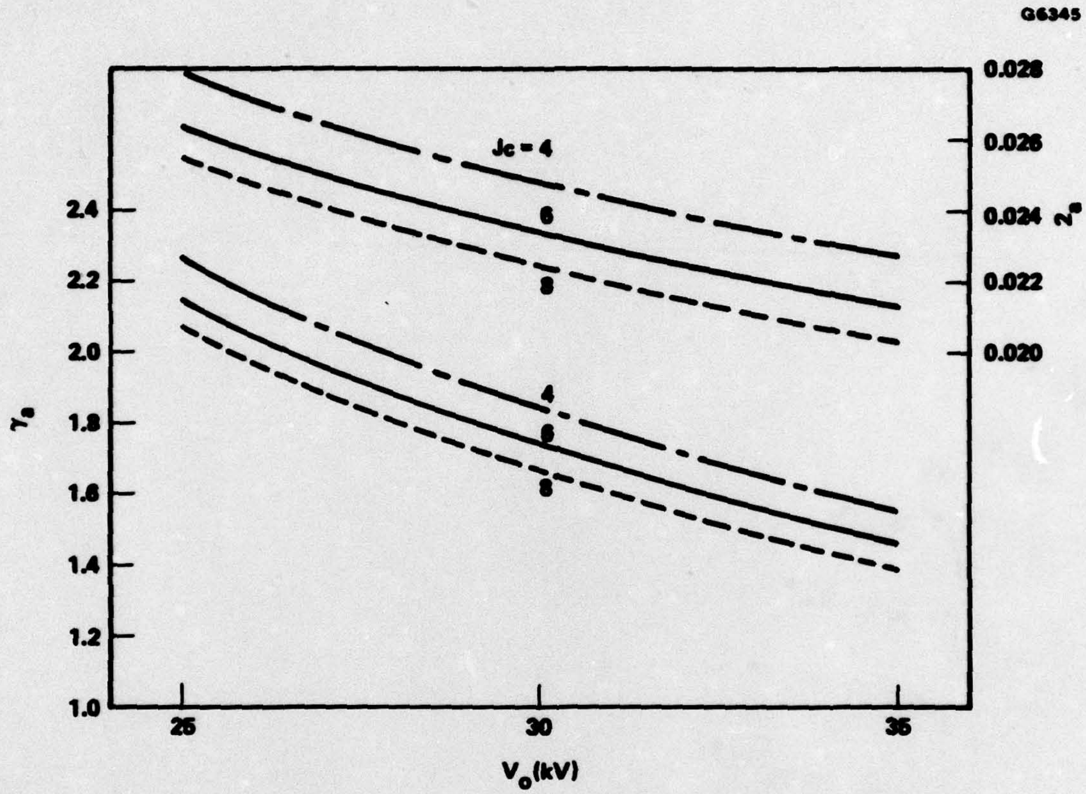

FIGURE 6 VARIATION OF γ_a AND Z_a WITH V_o FOR A 500 W TWT WITH DIFFERENT CATHODE LOADINGS.

TABLE IX

DESIGN PARAMETERS FOR A 93.75 GHz TWT
POWER OUT = 1000 W BEAM VOLTAGE = 40 kV
BEAM CURRENT = 500 mA PERVEANCE = .0625 μP

Current Density (A/cm^2)	J_C	6	8		
Cathode radius (in)	τc	.0641	.0555		
Beam hole diameter (in)	2a	.0250	.0241		
γa		1.601	1.543		
C		.02603	.02683		
Peak field (gauss)	Bp	5300	5330		
Magnetic period (in)	L	.457	.460		

TABLE X

DESIGN PARAMETERS FOR A 93.75 GHz TWT
POWER OUT = 1000 W BEAM VOLTAGE = 45 kV
BEAM CURRENT = 444 mA PERVEANCE = .0466 μP

Current Density (A/cm^2)	J_C	6	8		
Cathode radius (in)	τc	.0604	.0523		
Beam hole diameter (in)	2a	.0233	.0224		
γa		1.404	1.350		
C		.02657	.02732		
Peak field (gauss)	Bp	5390	5420		
Magnetic period (in)	L	.468	.472		

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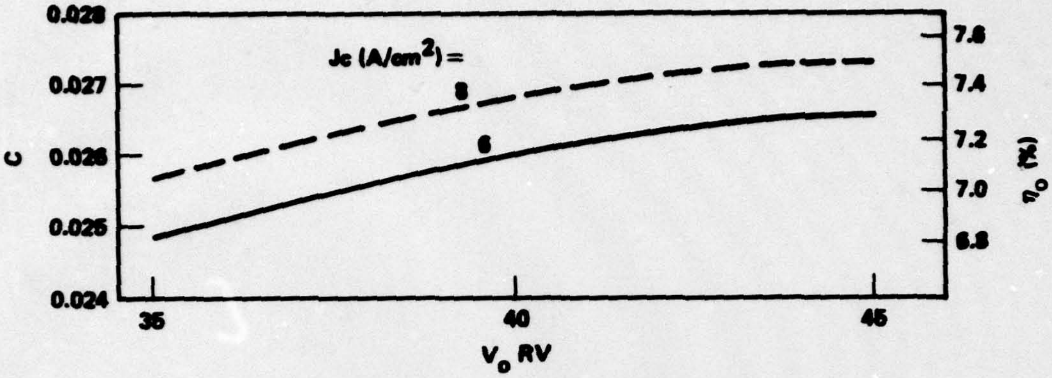

FIGURE 7 VARIATION OF C AND η_0 WITH V_0 FOR A 1000 W TWT WITH DIFFERENT CATHODE LOADINGS.

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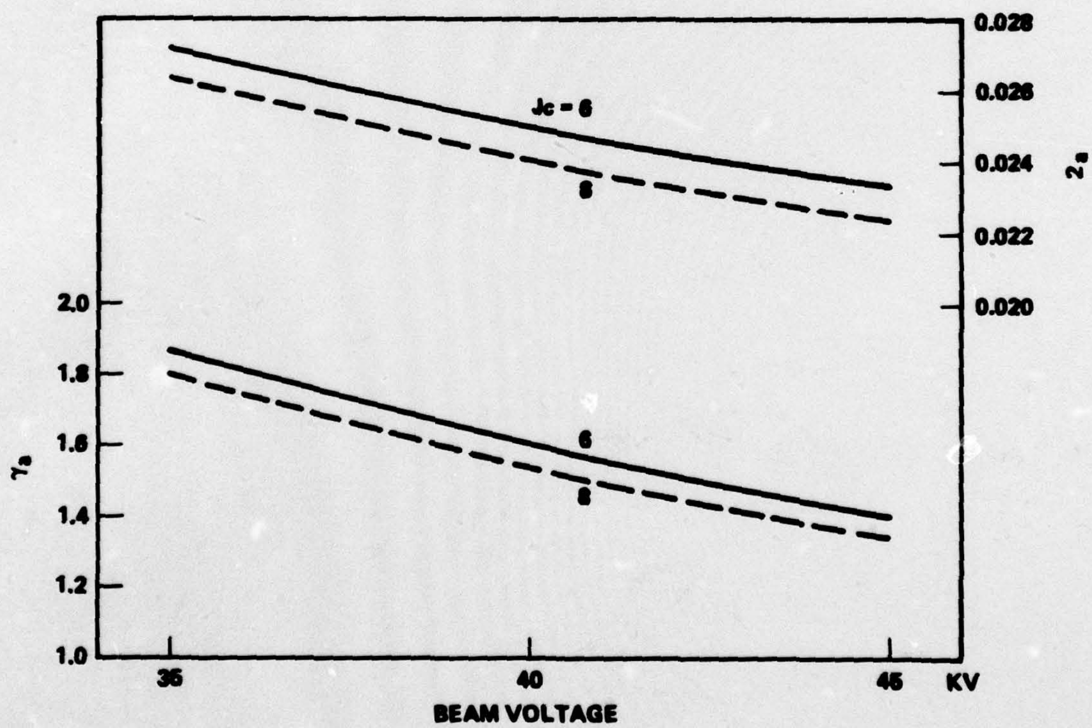

FIGURE 8 VARIATION OF γ_a AND 2_a WITH V_0 FOR A 1000 W TWT WITH DIFFERENT CATHODE LOADINGS.

3. SUMMARY

Comparison of the parametric values for the four tube designs from 100 W to 1000 W at 93.75 GHz give a clear estimate of the magnitude of the design problem, particularly in terms of magnetic focusing and where bandwidth are concerned. For example, the 200 W TWT can expect a bandwidth of 2.35% at 93.75 GHz with a cathode loading of $2 A/cm^2$, which rises to 2.97% at $J_c = 4\ A/cm^2$. While values of J_c up to $8\ A/cm^2$ are used, the higher the current density, the higher the operating temperature, and the lower the expected cathode life. Further, as the cathode temperature increases, evaporation of Barium increases, resulting in a greater likelihood of arcing in the electron gun.

For the 100 W design, the probable characteristics are as follows:

Frequency	93.75 GHz (91.875 to 95.625 GHz obj.)
Power	100 W
Gain	50 dB
Duty	50%
Modulation	Aperture grid
Cathode voltage	-22 kV
Cathode current	91 mA
Collector voltage	-14 kV
Collector current	91 mA
Body voltage	Ground
Body current	<10mA
Grid bias voltage	-1100V
Grid pulse voltage	+1100V
Grid current	Negligible
Heater voltage	6V
Heater current	1A

Size	4" dia x 16"
Weight	14 - 15 lbs
Focusing	PPM (SmCo)
Cooling	Liquid

Gun Parameters

Perveance	$.028 \times 10^{-6}$
Convergence ratio	83
Beam size	7.35 mils
Beam voltage	22 kV
Cathode diameter	.067 in
Cathode loading	4 A/cm^2

Magnetic Focusing Parameters

Peak field an axis	4450 gauss
Pole piece id	.170 - .200"
Pole piece od	1.5"
Magnetic period	.374"
λ_s/L	1.2

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1 DELSD-AS
1 DELSD-L (TECH LIB)
2 DELSD-L-S (STINFO)
25 DELET-TL-B (FISCHER)

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001 DOVER, NJ 07801

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GEORGIA TECH/EES
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001 ATLANTA, GA 30332

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ATTN: DRDAR-SCF-IM (MR. YAROSH)
001 DOVER, NJ 07801

COMMANDER
AARADCOM
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PALO ALTO, CA 94304

COMMANDER
NAVAL OCEAN SYSTEMS COMMAND
ATTN: R. WILLS, CODE 8212
271 CATALINA BLVD.
001 SAN DIEGO, CA 92152

DR. PAUL COLEMAN
UNIVERSITY OF ILLINOIS
001 URBANA, ILLINOIS

DR. RICHARD GROW
UNIVERSITY OF UTAH
ELECTRICAL ENGINEERING DEPT.
001 SALT LAKE CITY, UT